JOINING MAGNESIUM ALLOYS TO CARBON FIBER REINFORCED POLYMERS

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DOE-VTO AMR

Project ID # MAT-139

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OVERVIEW

Timeline

- Start: FY18
- Finish: FY20
- Percent complete: 50%

Budget

- Total project funding
  - DOE share – $1.8M
  - Contractor share - None
- 50/50 PNNL/ORNL
  - FY18 - $600K
  - FY19 - $600K

Barriers

- Magnesium (Mg) to carbon fiber reinforced polymer (CFRP) joints are limited by:
  - Lack of high-volume joining processes[1]
  - Galvanic corrosion[2]
  - Lack of design knowledge

[1]Pg. 3, U.S. DRIVE Materials Technical Team Roadmap, October 2017
[2]Pg. 8, U.S. DRIVE Materials Technical Team Roadmap, October 2017

Partners

- Pacific Northwest National Laboratory
- Oak Ridge National Laboratory
- BASF

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RELEVANCE

- **Impact**
  - Research advanced technologies for joining metals to composites
  - Improve understanding of metal to composite materials joints
- **Objectives**
  - Develop new techniques for joining Mg sheet to CFRP
  - Improve joint performance compared to existing dissimilar joining techniques
- **Relevance to VTO**
  - Enable widespread use of Mg-CFRP joining technologies for automotive light-weighting

MILESTONES

Milestone	Due Date	Status
Down-select technologies for investigation in FY19	September 2018	Completed
Task 1: Develop FSW tool geometry and process parameters to improve mixing between Mg sheet and Mg pins. Validate mixing quality by microstructural characterization	September 2019	Ongoing
Task 2: Evaluate mechanical joint performances and study corrosion performance of Mg-CFRP joint interface	September 2019	Ongoing

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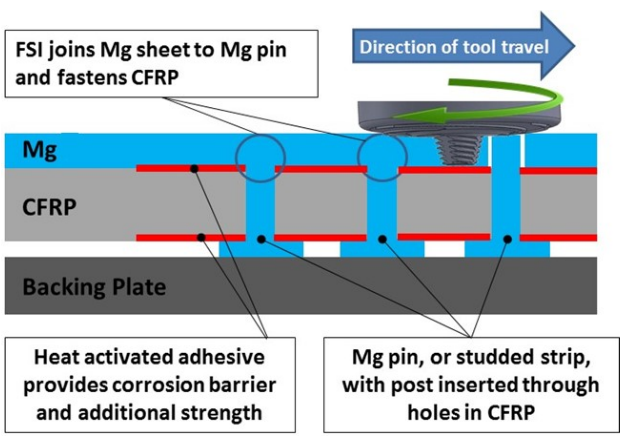
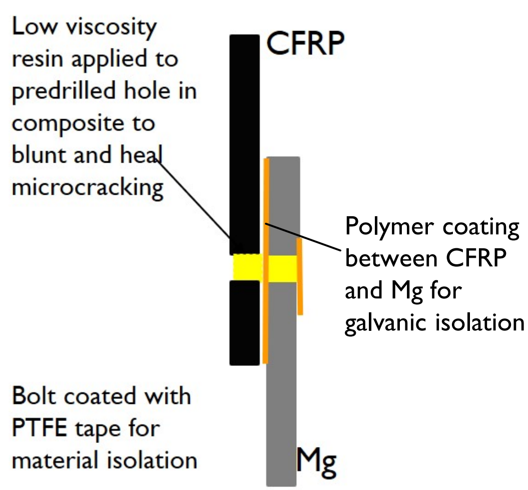
APPROACH

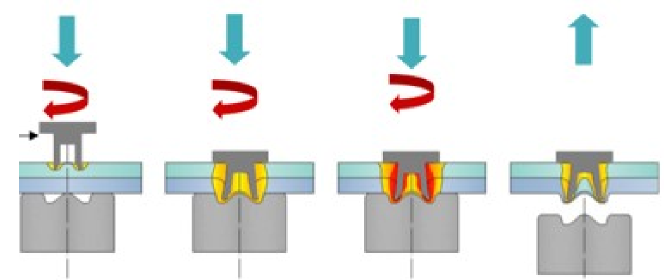
- **Investigate four joining technologies that involve mechanical interlocking**
  - Task 1: Friction Stir Interlocking (FSI) — PNNL Lead
  - Task 2: Bolting and Friction Self-Piercing Rivet — ORNL Lead
  - Task 3: Magnesium Overcasting — PNNL Lead
  - Task 4: Ultrasonic Joining — ORNL Lead

TASKS 1 AND 2 DOWN-SELECTED AFTER REVIEW



Task 1: FSI





Task 2: Bolting and F-SPR

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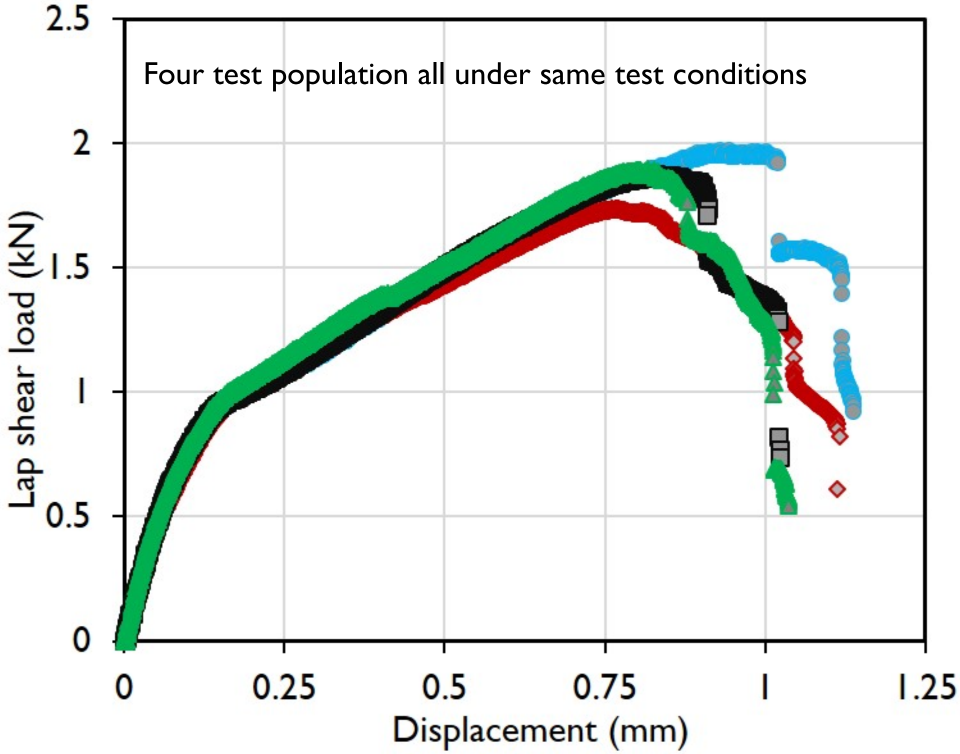
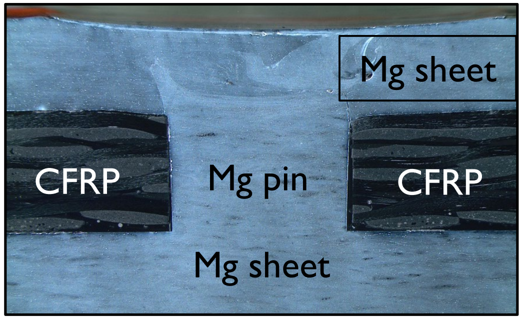
ACCOMPLISHMENTS: TASK 1
MG TO CFRP FSI WELD PERFORMANCE

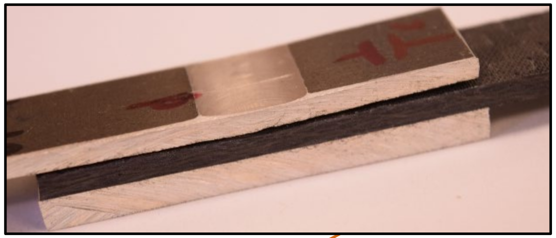


Load as a function of displacement for the lap shear testing of Mg-TS CFRP joints with an average thickness of ~0.5"

- Maximum normalized joint strength of 100 MPa

- Easy to weld
  - Thermoset plastic (TS)-CFRP does not deflect at weld conditions
- Defect free welds
- Cone/cup failure in Mg pin





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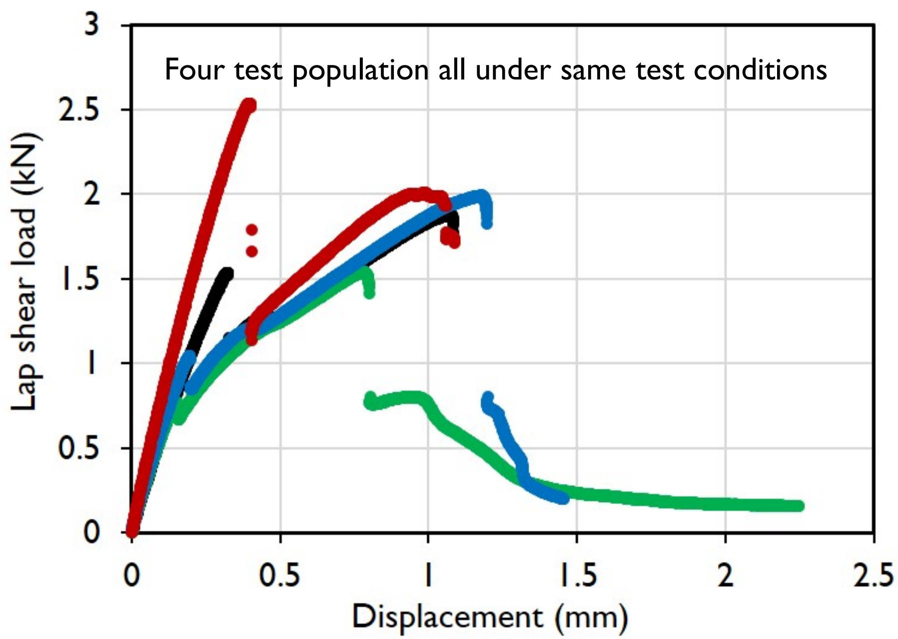
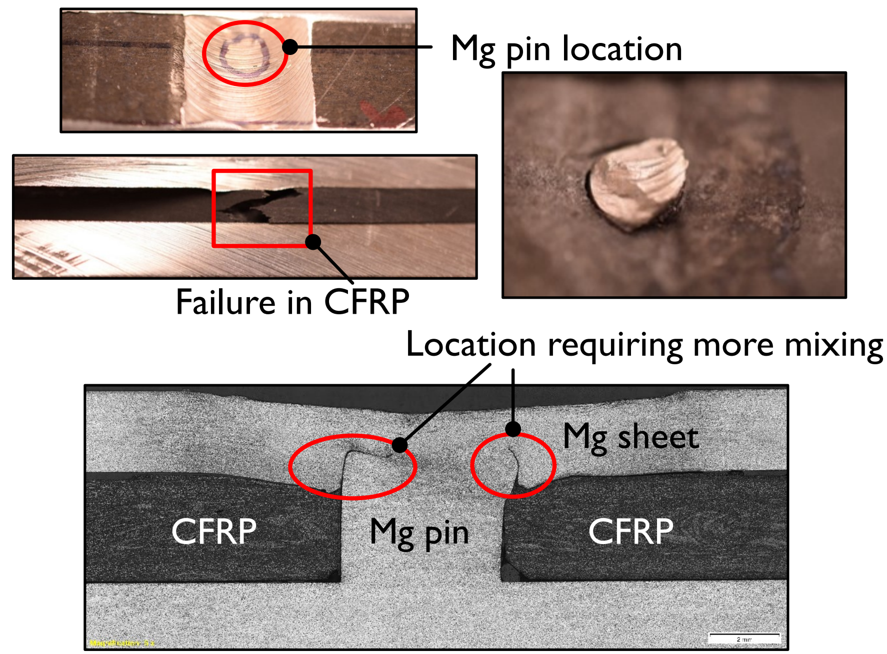
ACCOMPLISHMENTS: TASK 1
MG TO CFRP FSI WELD PERFORMANCE



Load as a function of displacement for the lap shear testing of Mg-TP CFRP joints with an average thickness of ~0.5"

- Common failure modes:
  - Net tension in thermoplastic (TP) CFRP
  - Cone/cup failure in Mg pin



- Maximum normalized joint strength of 130 MPa
- Limited weld defects
- Limited pin/plate mixing

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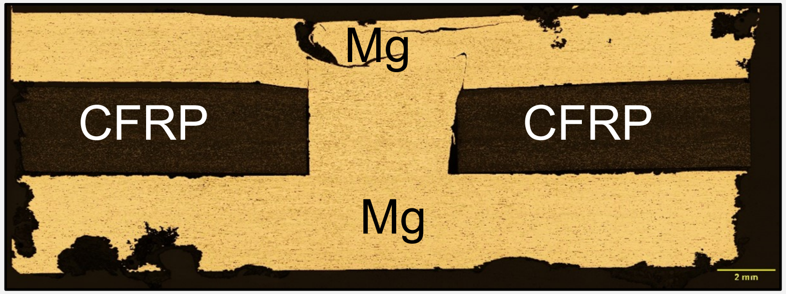
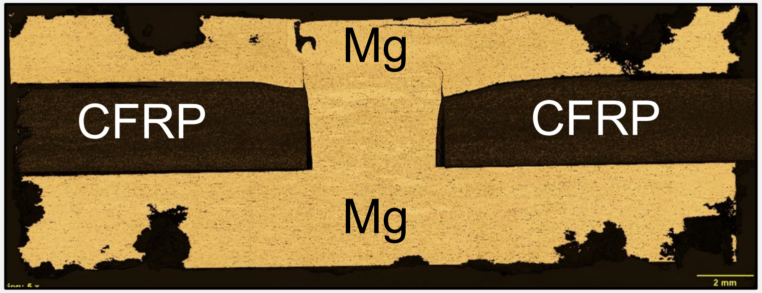
ACCOMPLISHMENTS: TASK 1
FSI JOINT CORROSION PERFORMANCE

- FSI welded Mg-TP CFRP samples testing for 250 h per ASTM B117

Without thermal bonding layer	With thermal bonding layer
	
- Surface defects may be pathway to interface - No corrosion at top interface - Corrosion at the bottom interface detected	- No corrosion at top interface similar to without-bonding layer sample - No corrosion at the bottom interface as well

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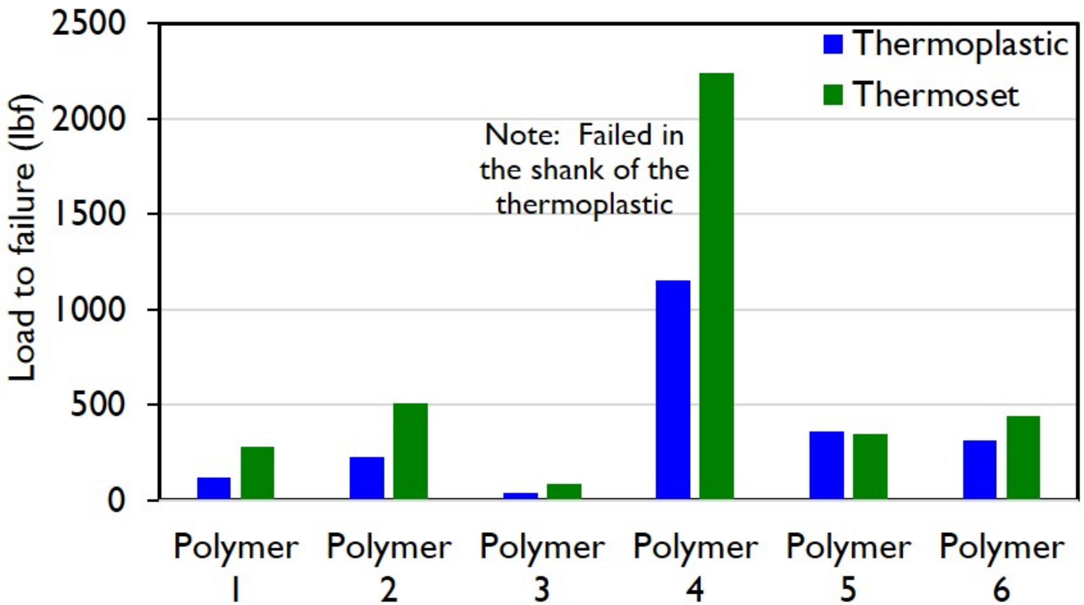
ACCOMPLISHMENTS: TASK 2-BOLTING

MG-CFRP BOLT PERFORMANCE WITH CRACK FILLING POLYMERS



Failure load for different polymer fillings for the lap shear testing of Mg-TP CFRP

- Screened 47 different polymers for filling in hole
- Polymer 4 is commercially available product available from DAP® Inc.

- Surface Isolation: Composite and magnesium samples at proof-of-concept scale "painted" with a thin coating of a quick set epoxy
- A MasterBond resin specifically designed for Mg "painted on" with a brush
- Bolt Isolation: Bolts received two wraps of PTFE pipe tape which is commercially used in natural gas pipelines

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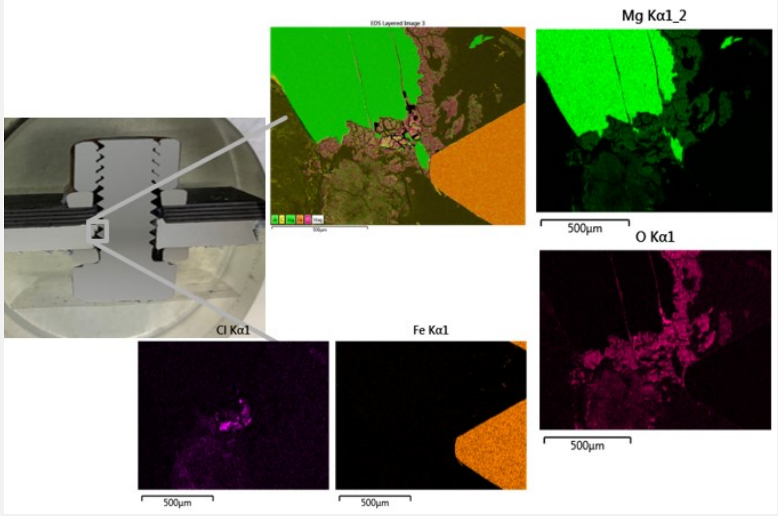
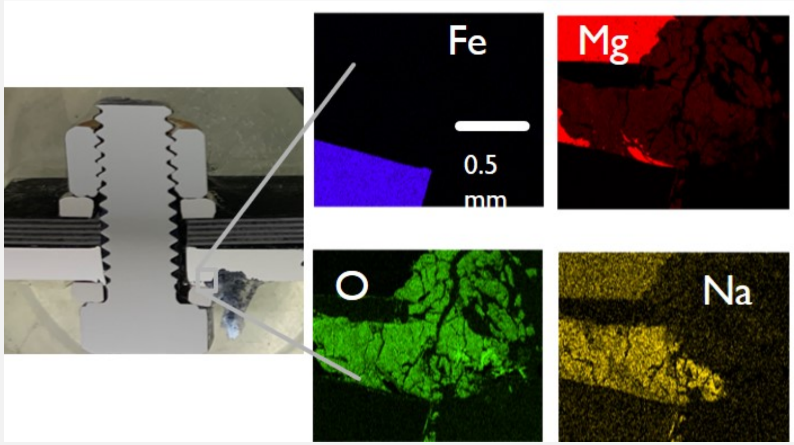
ACCOMPLISHMENTS: TASK 2-BOLTING MG-CFRP BOLT CORROSION TESTING

Mg/CFRP bolted lap joint unmodified corroded for 100 hours	Mg/CFRP bolted lap joint modified corroded for 100 hours
	
➢ Corrosion observed at the Mg-steel bolt interface inside the joint	➢ Galvanic corrosion observed near the Mg-washer interface only

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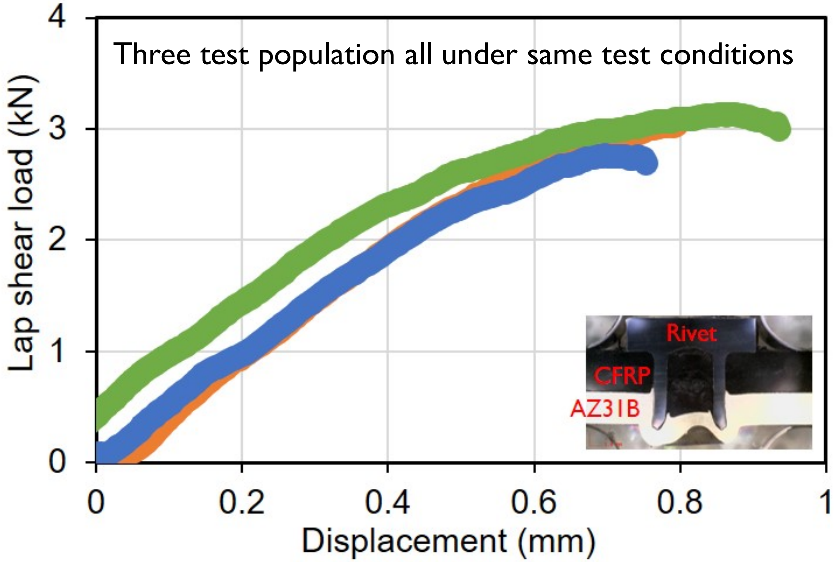
ACCOMPLISHMENTS: TASK 2-BOLTING
BOLTING TEST RESULTS SUMMARY

Joint Type (All joints with 6 mm bolt)	Composite	Ultimate Load (kN)	Normalized Load (N/mm^2)
Uncorroded Baseline	Thermoset	5.6 – 6.2	595 – 658
Corroded Baseline after 100-hour corrosion exposure.	Thermoset	4.9 – 5.0	520 - 531
Modified with healing resin and isolating layer after 100-hour corrosion exposure.	Thermoset	6.3 – 6.8	669 – 722
Uncorroded Baseline	Thermoplastic	4.9 – 5.1	520 - 541
Corroded Baseline after 100-hour corrosion exposure.	Thermoplastic	4.8 – 4.9	509 - 520
Modified with healing resin and isolating layer after 100-hour corrosion exposure.	Thermoplastic	5.0 – 5.5	531 - 584
Modified with healing resin epoxy adhesive (XP0012) as the isolating layer. No Corrosion.	Thermoset	9.9 – 10.0	15.3 – 15.5
Modified with healing resin acrylic adhesive (810) as the isolating layer. No Corrosion.	Thermoset	11.0 – 12.3	17.1 – 19.1

Effective area of the bolted with isolating is the area of the bolt. (Area= 9.42 mm^2)
Effective area of the bolted plus adhesive is 25.4mm x 25.4 mm (645.16 mm^2)
All samples had the healing resin applied.

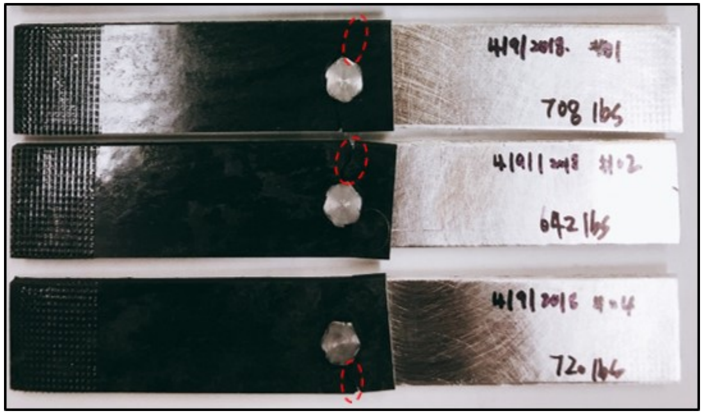
ACCOMPLISHMENTS: TASK 2 F-SPR
MG TO TP-CFRP F-SPR WELD PERFORMANCE



Load as a function of displacement for the lap shear testing of Mg-TP CFRP

Sample	Lap shear load (kN)	Peak failure load/ rivet diameter (N/mm)	Absorbed energy (J)
#01	3.15	594.22	1.23
#02	2.86	538.22	1.23
#03	3.2	604.29	2.27
Avg.	3.07 ± 0.19	579 ± 35.25	1.58 ± 0.6

- No cracks observed in AZ31B after rivet pierced and formed
- All samples failed near hole in thermoplastic CFRP
  - Localized tensile failure ~ w/d
  - Widening CFRP can increase joint strength



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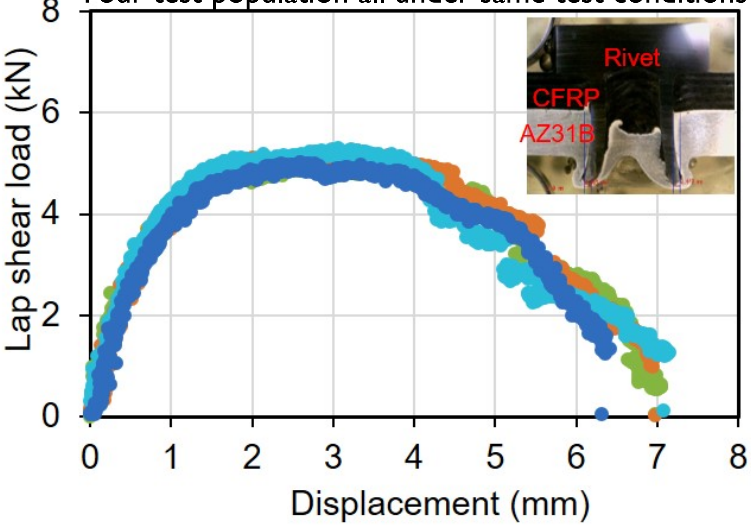
ACCOMPLISHMENTS: TASK 2 F-SPR
MG TO TS-CFRP F-SPR WELD PERFORMANCE



Load as a function of displacement for the lap shear testing of Mg-TS CFRP

Sample	Lap shear load (kN)	Peak failure load/ rivet diameter (N/mm)	Absorbed energy (J)
#06	5.12	966.86	26.44
#09	5.27	993.72	27.03
#10	5.3	1000.43	26.39
#11	5.04	950.07	24.33
Avg.	5.18 ± 0.12	977.77 ± 23.48	26.05 ± 1.18

- Elongation at failure was 6-7 mm
- Highest strength joints failed by rivet pullout from AZ31B

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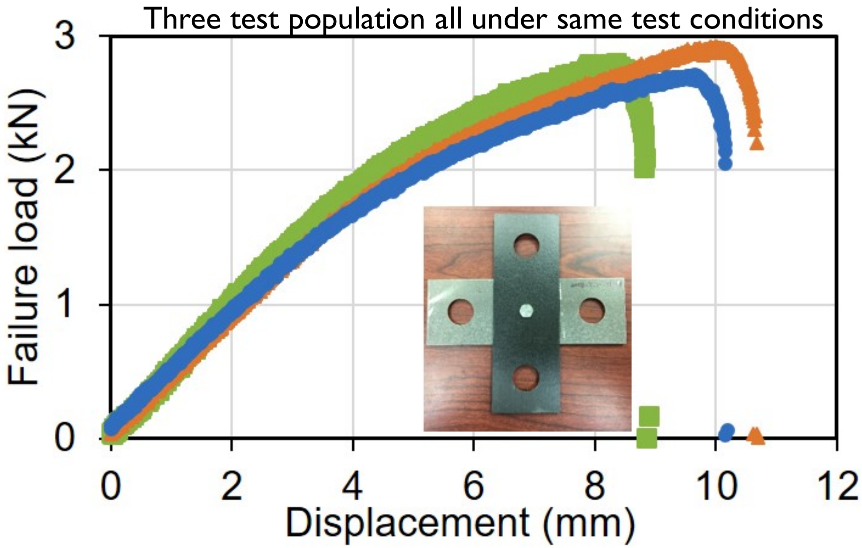
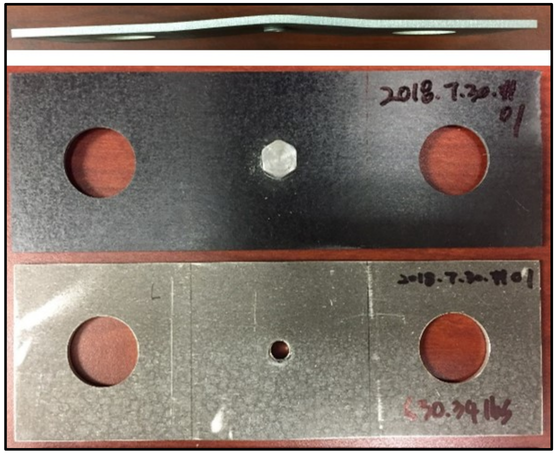
ACCOMPLISHMENTS: TASK 2
MG TO TP-CFRP F-SPR WELD PERFORMANCE



Load as a function of displacement for the cross-tension testing of Mg-TP CFRP

Sample ID	Peak failure load (kN)	Absorbed energy (J)	Elongation at failure (mm)
#01	2.80	15.7	8.88
#02	2.92	20.02	10.69
#03	2.71	18.02	10.19
Average	2.81±0.11	17.91±2.16	9.92±0.93

- AZ31B pullout failure mode for corroded and control samples
- AZ31B significantly deformed before failure
- Good mechanical interlocking at the joint interface



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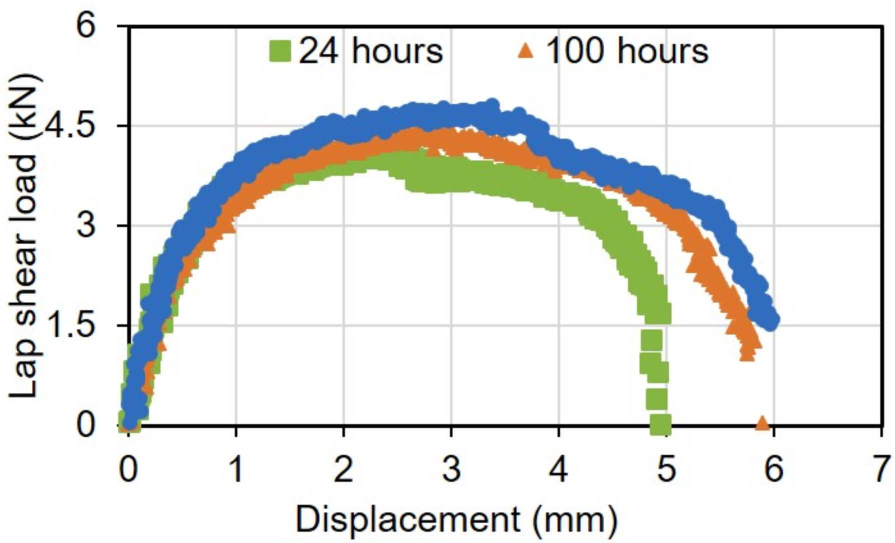
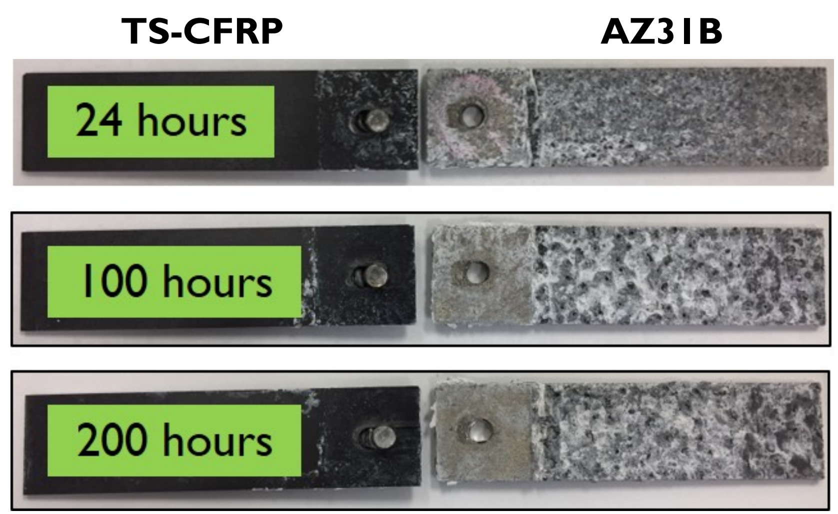
ACCOMPLISHMENTS: TASK 2
MG TO TS-CFRP F-SPR CORROSION TESTING



Corrosion time (hours)	Lap shear failure load (kN)	Peak failure load/ rivet diameter (N/mm)
0	5.07 ± 0.11	955.86 ± 19.84
24	4.23	799.3
100	4.48	845.2
200	4.81	908.0



- AZ31B pullout failure mode for corroded and control samples
- Significant general corrosion of AZ31B observed with increasing corrosion exposure time
  - Corrosion at joint interface not severe compared to general corrosion of AZ31 surface

RESPONSES TO PREVIOUS YEAR'S REVIEWERS' COMMENTS

Comment	Response
No discussion of adhesives for joining	PNNL is addressing this aspect in a parallel research project.
In addition to lap shear, target additional testing	ORNL performed cross-tension testing in FY19. Fatigue testing at ORNL is planned; will be executed in FY19&20. Peel testing at PNNL is planned; will be executed in FY20.
Define target applications early to ensure project success No industry partners; no component or full-scale testing	The Joining Core Program is focused on early-stage research to establish foundational knowledge about dissimilar material interfaces. The intent is to leverage this core knowledge and apply to application specific projects in conjunction with industry, but as separately established projects as commercial partners define.

COLLABORATION AND COORDINATION

- Pacific Northwest National Laboratory
  - Keerti Kappagantula (Task 1 Lead), Piyush Upadhyay, Scott Whalen, Tianhao Wang
- Oak Ridge National Laboratory
  - David Warren (Task 2 Lead), Yong Chae Lim, Jian Chen, Jiheon Jun
- BASF – Thermoplastic plaques provided

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REMAINING CHALLENGES AND BARRIERS

- Task 1: Friction Stir Interlocking
  - Limited Mg pin/sheet mixing
  - TP-CFRP deflection during welding

- Task 2: Friction Self-Piercing Rivet
  - Residual stresses between rivet and Mg sheet at interface
  - Limited corrosion resistance

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PROPOSED FUTURE WORK

- Task 1: Friction Stir Interlocking
  - Improve Mg pin/sheet mixing through tool and process optimization
  - Mitigate corrosion at interface through weld-bonding
  - Identify dominant joint failure mechanisms

- Task 2: Friction Self-Piercing Rivet
  - Determine effects of coating and weld-bonding on corrosion
  - Evaluate hole spacing and interfacial residual stress effects

Future work is subject to change based on funding levels

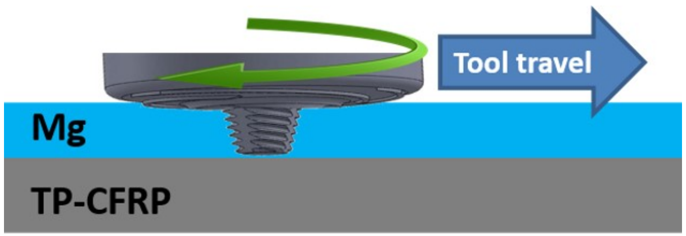
SUMMARY

- Task 1: Friction Stir Interlocking
  - Demonstrated FSI of AZ31 to TP-CFRP and Mg to TS-CFRP
  - Completed lap shear and corrosion testing of FSI Mg-CFRP joints with and without thermal bonding layer
- Task 2: Bolting and Conventional Mechanical Interlocking
  - Demonstrated bolting of thick AZ31 to thick TS-CFRP using 0.5″ bolts.
  - Completed lap shear and corrosion testing of Mg-CFRP bolted joints
- Task 2: Friction Self-Piercing Rivet
  - Demonstrated F-SPR of AZ31B to TP-CFRP and Mg to TS-CFRP
  - Completed lap shear, cross-tension and corrosion testing of Mg-CFRP F-SPR joints

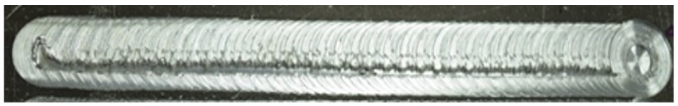
TECHNICAL BACKUP SLIDES

FRICTION STIR INTERLOCKING PROCESS DEVELOPMENT

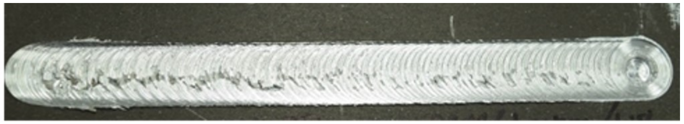
➢ **Stage 1:** Mg-CFRP bead on plate (BoP)



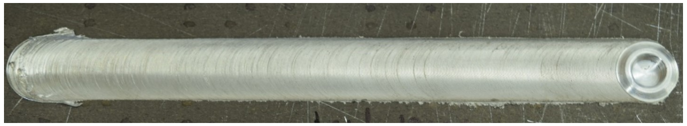
Mg on TP-CFRP

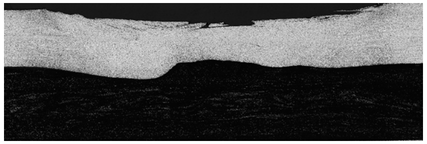


Process optimization



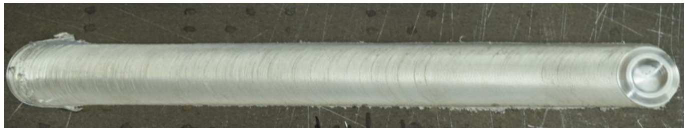
Process + Tool design optimization





Mg on TS-CFRP

Process optimization



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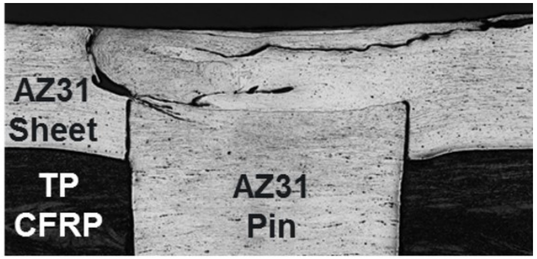
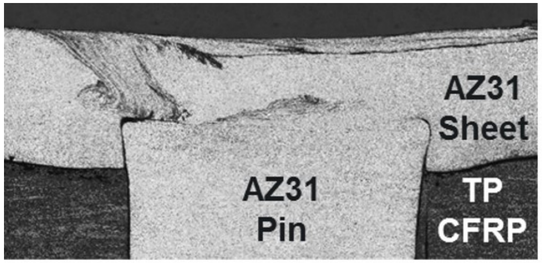
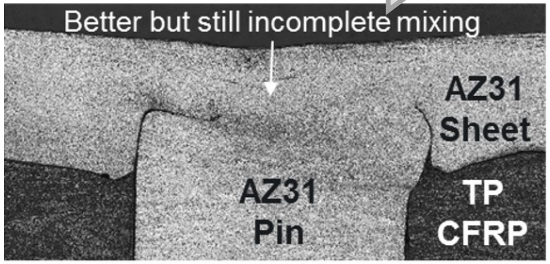
FRICTION STIR INTERLOCKING PROCESS DEVELOPMENT

- **Stage 2:** FSI with optimized BoP tool and parameters

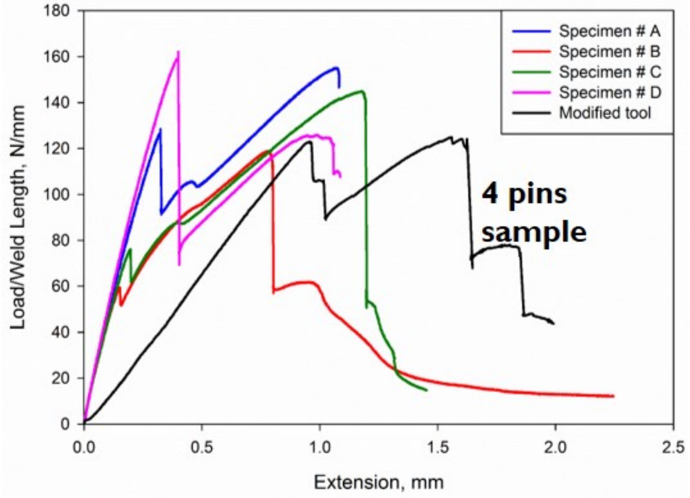
Increased but incomplete Mg sheet – Mg pin mixing



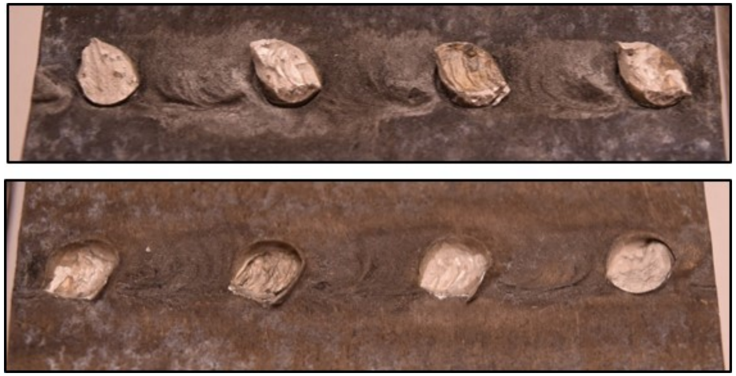




Mg/TP-CFRP FSI joint



Lap shear testing of FSI welded Mg/TP-CFRP plates joined with four Mg interlocks



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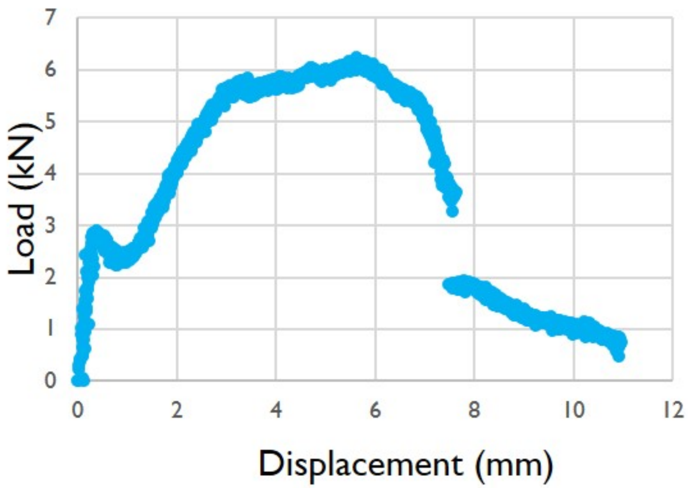
TASK 2: BOLTING AND CONVENTIONAL MECHANICAL INTERLOCKING – RESULTS

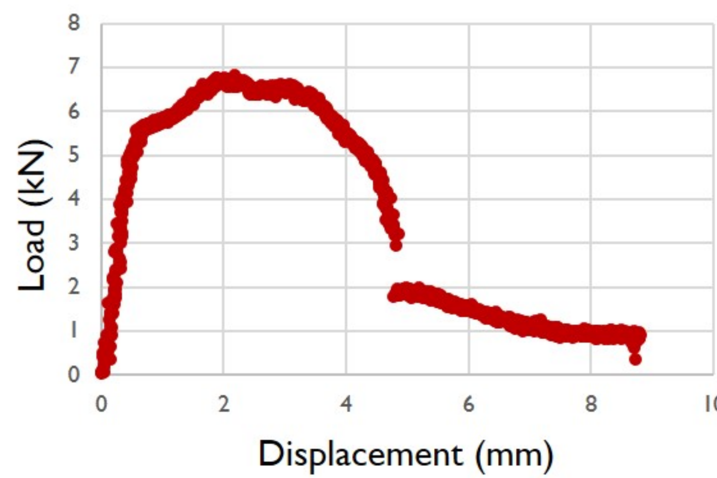


Baseline (Uncorroded) Bolted CFC (Thermoset and AZ31) 6 mm Bolt

Peak Load: 1406-1536 lbf
Peak Stress: 6.3-6.8 kN
Energy Absorbed: 31.4-32.5 J

Peak Load: 1262-1403 lbf
Peak Stress: 5.6-6.2 kN
Energy Absorbed: 32.8-33.5 J

Modified and Corroded after 100 hours Bolted CFC (Thermoset and AZ31) 6 mm Bolt



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TASK 2: BOLTING AND CONVENTIONAL MECHANICAL INTERLOCKING – FUTURE/CURRENT WORK

- Proof of Concept Phase – Exploratory (Completed)
- Determine Corrosion exposure times to yield baseline change
- Test modified samples at and above that vs baseline
- Repeat for cross-tension

- Current Phase - Development
- Use only thermoset composite
- Use only one hole generation method
- Work with Supplier to arrive at a final healing material that can withstand paint bake cycles. (DAP)
- Work with Supplier to arrive at a final coating material for maximum adhesion and to withstand paint bake cycles. (Masterbond)
- Since at least 2 OEMs are trying to develop ladder structures with CFC and AHSS:
  - Shift to a CFC (epoxy and fiber architecture that is relevant chose ± 45)
  - Consider using coated Mg rather than bare which may eliminate coating
  - Consider introducing AHSS as well (Future work)
- Test coated with and without healing resin to separate the effects.
- Publish 3 papers

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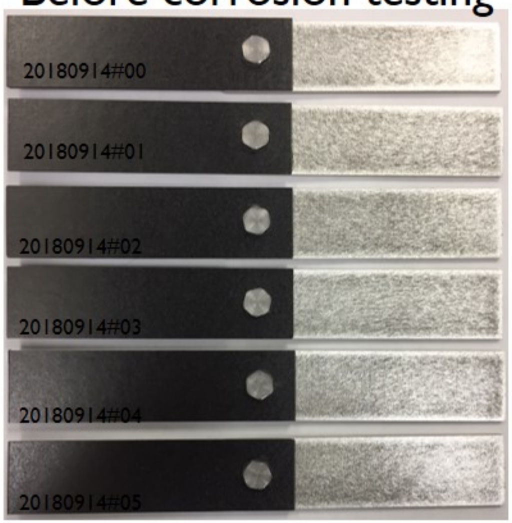
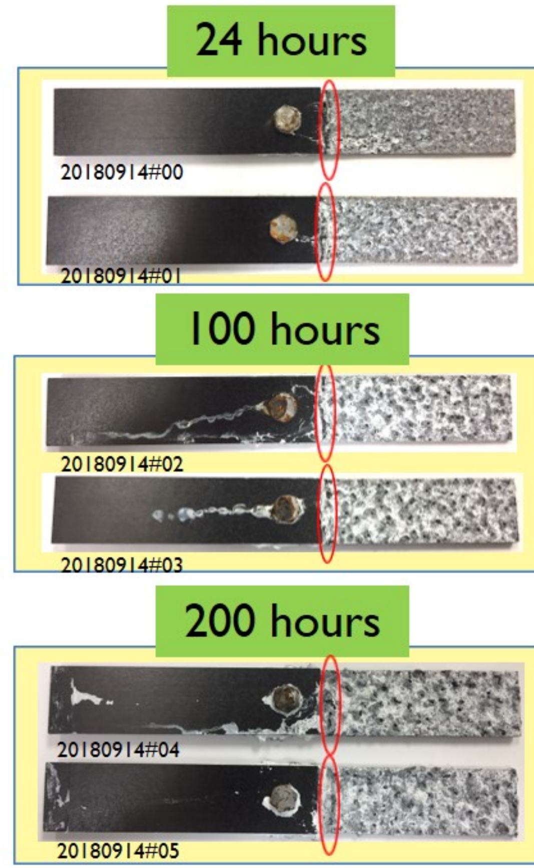
CORROSION TESTING OF F-SPR SPECIMENS

Before corrosion testing



Corrosion testing (ASTM B117) at ORNL



- AZ31B surface was progressively corroded as increased corrosion exposure time
  - Localized corrosion on AZ31B was observed (red circle)
- Top of steel rivet was slightly corroded, while corrosion of CFRP (TS) was negligible

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PUBLICATION AND PRESENTATIONS

- Piyush Upadhyay, Reza E Rabby, Scott Whalen, Joining of Magnesium to Reinforced Polymers Using Friction Stir Interlocking. TMS conference, March 10~14th, 2019, San Antonio, Texas
- Yong Chae Lim, Charles David Warren, Jian Chen, Zhili Feng. Joining of Carbon Fiber Reinforced Composite to Magnesium Alloy by Friction Self-Piercing Rivet. FABTECH and AWS conference, November 5~8th, 2018, Atlanta, Georgia
- Yong Chae Lim, Charles David Warren, Jian Chen, Zhili Feng. Joining of Lightweight Dissimilar Materials by Friction Self-Piercing Rivet. TMS conference, March 10~14th, 2019, San Antonio, Texas